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NATO Committee on the Challenges of Modern Society, Brussels (Belgium)

Prepared for

Environmental Protection Agency, Washington, DC

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OTAN CCMS

COMMITTEE ON THE CHALLENGES
OF MODERN SOCIETY

PB 295001

Flue Gas Desulfurization Pilot Study Phase I — Survey of Major Installations - Summary of Survey Reports on Flue Gas Desulfurization Processes

Report No. 95

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16. ABSTRACT Appendices to this summary consist of twelve individual status reports that will be available through the National Technical Information Service (NTIS) in the United States and of course limited copies will be available through NATO. The twelve report titles which are appendices to the summary are: (A) Status report on the Limestone/Sludge Flue Gas Desulfurization Process; (B) Status Report on the Lime/Sludge Flue Gas Desulfurization Process; (C) Status Report on the Double Alkali/Sludge Flue Gas Desulfurization Process; (D) Status Report on the Sea Water Scrubbing Flue Gas Desulfurization Process; (E) Status Report on the Limestone/Gypsum Flue Gas Desulfurization Process; (F) Status Report on the Lime/Gypsum Flue Gas Desulfurization Process; (G) Status Report on the Double Alkali/Gypsum Flue Gas Desulfurization Process; (H) Status Report on Flue Gas Desulfurization by Scrubbing with Dilute Sulfuric Acid; (I) Status Report on the Magnesium Oxide Flue Gas Desulfurization; (J) Status Report on the Sodium Sulfite Scrubbing Flue Gas Desulfurization Process; (K) Status Report on the Carbon-Adsorption Flue Gas Desulfurization Process; (L) Status Report on the Copper Oxide Flue Gas Desulfurization.

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Flue Gas Desulfurization Pilot Study Phase I

Survey of Major Installations - Summary of Reports on Flue Gas Desulfurization Processes

January 1979

Report No. 95

1(a)

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Appendices to this summary consist of twelve individual status reports that will be available through the National Technical Information Service (NTIS) in the United States and of course limited copies will be available through NATO. The twelve report titles which are appendices to the summary are:

A Status Report on the Limestone/Sludge Flue Gas Desulfurization Process

B Status Report on the Lime/Sludge Flue Gas Desulfurization Process

C Status Report on the Double Alkali/Sludge Flue Gas Desulfurization Process

D Status Report on the Sea Water Scrubbing Flue Gas Desulfurization Process

E Status Report on the Limestone/Gypsum Flue Gas Desulfurization Process

F Status Report on the Lime/Gypsum Flue Gas Desulfurization Process

G Status Report on the Double Alkali/Gypsum Flue Gas Desulfurization Process

H Status Report on Flue Gas Desulfurization by Scrubbing with Dilute Sulfuric Acid

I Status Report on the Magnesium Oxide Flue Gas Desulfurization

J Status Report on the Sodium Sulfite Scrubbing Flue Gas Desulfurization Process

K Status Report on the Carbon-Adsorption Flue Gas Desulfurization Process

L Status Report on the Copper Oxide Flue Gas Desulfurization

PREFACE

This report summarizes information on 12 flue gas desulfurization (FGD) processes as presented in separate Status Reports prepared by NATO-CCMS FGD study group during 1977. These reports, which form Appendices A through L, provided a brief review of the design and operating features of each system, its current status, problem areas, and limited cost data. In addition to general descriptive information, data for selected operational systems were also presented.

Most FGD processes have a number of design alternatives and a range of operating parameters. The information in these reports contains only general descriptions and not specific design parameters. Such design parameters can only be developed after site-specific information is made available. Although FGD cost data are presented, the variability in site-specific conditions and the nonuniformity in reporting cost information make costs for FGD processes very difficult to compare. Such conditions include variations in monetary inflation rates, the type of equipment and number of spares purchased, labor costs, and currency exchange rate variations.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENT	ii
PREFACE	v
1. Introduction	1-1
1.1 State of the Art	1-1
1.2 Purpose of Summary	1-3
1.3 Sources of Information	1-3
2. Process Descriptions	2-1
3. Current Status of Operating FGD Systems	3-1
3.1 Processes	3-1
3.2 Gypsum Processes	3-4
3.3 Regenerative Processes	3-5
4. Costs and Energy Requirements	4-1
4.1 FGD Process Costs	4-1
4.2 Energy Requirements	4-4
5. Process Aspects Needing Special Attention	5-1
5.1 Process Design and Operation	5-1
5.2 Fuel Chlorine Content	5-3
5.3 Scaling Problems	5-3
5.4 Other Environmental Impacts	5-4
6. Applicability Study	6-1

1.0 INTRODUCTION

1.1 STATE OF THE ART

The first commercial application of FGD to power plant sulfur oxide control was in the United Kingdom in the early 1930's. The Battersea A Power Plant (228 MW) of the London Power Company, London, UK, began flue-gas washing in 1933. The process utilized wet scrubbing with Thames River water providing most of the alkaline absorbent. The spent absorbent was discharged back into the Thames after settling and oxidation. The FGD system operated successfully at up to 95 percent SO_2 removal efficiency until the A Power Plant closed down in 1975. A similar FGD system operated on the Battersea B Power Plant (245 MW) between 1949 and 1969, when FGD operation was temporarily suspended because of adverse effects on the Thames water quality.

The ICI Howden process, also developed in England, was developed to avoid discharging scrubber effluent into the Thames. A solid sludge was produced and barged to sea for dumping. This process was applied to the Swansea Power Plant in 1935 and the Fulham Power Plant in 1937. These systems operated successfully until early World War II when they were shut down.

The next FGD unit was installed at the Electrolytic Zinc Company in Tasmania in 1949. Tidal water was used there as the absorbent for SO_2 from smelter gas.

In 1952 the first unit of the new oil-fired Bankside Power Station in London, UK, was commissioned. This FGD system is an improved version of the Battersea system, using water from the

Thames. This system is still operating at up to 98 percent removal efficiency and with a present capacity of 240 MW.

The 1950's and 1960's were a time of laboratory and pilot plant investigations of new processes. During the 1950's the Tennessee Valley Authority (USA) investigated lime/limestone systems, both dry and wet, and dilute acid processes; in Germany the first major carbon adsorption processes were developed. During the 1960's the magnesium oxide, copper oxide, and sulfite scrubbing processes were investigated among others.

Lime/limestone processes were installed in 1964 on an iron ore sintering plant in Russia and on a large sulfuric acid plant in Japan in 1966.

In 1966 Combustion Engineering developed a dry limestone injection process, which was installed at five boilers in the United States by 1972. Because of major problems associated with dry limestone injection including plugging (especially of the boiler tubes), low sulfur dioxide removal, and reduced particulate collection in the electrostatic precipitators, these systems proved inadequate. The five installations are now either closed down or converted to other control systems.

Japan has at present the largest installed capacity of FGD systems. Most of these systems were built between 1975 and 1977. Systems based on lime/limestone predominate. As of December 1977, the United States had 27 operating utility units treating about 35 X 10^6 Nm^3/h*(10 GW), 34 units under construction to treat 50 x 10^6 Nm^3/h (14.2 GW), and 20 units planned to treat 34

*Normal conditions are 0 °C. and 1 bar.

x 10^6 Nm^3/h (9.7 GW); in addition 25 industrial boilers were operational or under construction with a capacity of about 5 x 10^6 Nm^3/h (1.5 GW). In the Federal Republic of Germany, approximately 775,000 Nm^3/h of flue gas are being treated by lime and carbon adsorption processes, and in Norway 155,000 Nm^3/h are treated by seawater scrubbers on oil-fired boilers.

1.2 PURPOSE OF SUMMARY

This report summarizes the NATO-CCMS FGD Status Reports into a single report for better comparison of the various FGD processes. Information is presented on process descriptions, current status of the processes, cost, energy consumption, and areas of special difficulty or of development. However, the individual Process Status Reports (listed in the bibliography) should be regarded as the principal source of information on these processes.

1.3 SOURCES OF INFORMATION

A detailed questionnaire, compiled by the NATO-CCMS study group, was sent to FGD process vendors and selected users. Information from the completed questionnaires was incorporated into draft Process Status Reports by consulting organizations acting for the pilot and co-pilot countries. The draft reports were reviewed by the study group and sent to process vendors and users, for further comment where applicable, before being prepared in final form. The FGD process and the various sources of information are summarized in Table 1.1.

Table 1.1. INFORMATION SOURCES FOR FGD PROCESSES

Process	Consultants	Comment obtained	
		User	Vendor
Limestone/sludge	P	Yes	Yes
Lime/sludge	A, B, P		
Double alkali/sludge	P		
Seawater scrubbing	S	Yes	Yes
Limestone/gypsum	A, P	Yes	
Lime/gypsum	A, B	Yes	Yes
Double alkali/gypsum	A, P		
Dilute sulfuric acid/gypsum (Chiyoda)	A, P		Yes
Sodium sulphite (Wellman-Lord)	A, P	Yes	Yes
Magnesium oxide	A, P	Yes	Yes
Carbon adsorption (Bergbau)	B	Yes	Yes
Copper oxide (Shell)	A, P		

A = Jumpei Ando, Chuo University, Japan
B = Battelle - Frankfurt, West Germany
P = PEDCo Environmental, USA
S - SINTEF, Trondheim University, Norway

NOTE: All data on processes operating in Japan were provided by Dr. Ando.

Published reports as listed in the individual Status Reports were also used to supplement information obtained from the questionnaires.

2.0 PROCESS DESCRIPTIONS

FGD processes can most conveniently and usefully be categorized by the manner in which the sulfur compounds removed from the flue gases are eventually produced for disposal. In this way three main categories result:

1. Throwaway processes, in which the eventual product is disposed of entirely as waste. Disposal can include landfill, ponding, discharge to water course or ocean, or discharge to a worked-out mine.

   All the surveyed processes in this category involve wet scrubbing of the flue gases for absorption, followed by various methods for neutralizing the acidity, separating the sulfur compounds from the scrubbing liquor, and usually recycling at least part of the scrubbing liquor.

2. Gypsum processes, which are designed to produce gypsum of sufficient quality either for use as an alternative to natural gypsum or as a well-defined waste product with good disposal characteristics.

   As with the throwaway processes, this category involves wet scrubbing for absorption followed by various methods of neutralizing with lime or limestone and recovering the sulfur compound. An oxidation step is included to insure recovery of the sulfur compounds in the form of gypsum.

3. Regenerative processes, which are designed specifically to regenerate the primary reactants and concentrate the sulfur dioxide that has been removed from the flue gases. Further chemical processing can then convert the concentrated SO_2 into sulfuric acid or elemental sulfur, or physical processing into liquified sulfur dioxide. The surveyed processes in this category contain both wet scrubbing and dry adsorption processes.

Tables 2.1, 2.2, and 2.3 present a summarized description of the surveyed processes in each of these 3 categories. The chemical reactions involved are given fully in Section 2 of each Process Status Report.

Table 2.1. SUMMARY DESCRIPTION OF FGD PROCESSES - THROWAWAY CATEGORY

FGD process (year of first use)	Primary reagent	Product for disposal	Operating principles	Present status
1 Limestone/sludge (1933)	$CaCO_3$	$CaSO_3/CaSO_4$ wet sludge	Flue gases scrubbed with limestone slurry. SO_2 reacts to form insoluble Calcium compounds, which are separated and partly dewatered for disposal.	Commercial operation (coal and oil), principally in USA.
2 Lime/sludge (1972)	CaO	$CaSO_3/CaSO_4$ wet sludge	Flue gases scrubbed with slurry of hydrated lime. SO_2 reacts to form insoluble Calcium compounds, which are separated and partly dewatered for disposal.	Commercial operation (coal and oil), principally in USA.
3 Double alkali/sludge (1974)	NaOH or Na_2CO_3 and CaO or $CaCO_3$	$CaSO_3/CaSO_4$ wet sludge	Flue gases scrubbed with alkaline sodium based compounds in solution. Used solution regenerated with lime or limestone in separate reactor to form insoluble Calcium compounds, which are separated and partly dewatered for disposal.	Recent commercial operation on industrial sized coal-fired boilers in USA.
4 Seawater scrubbing (1975)	Seawater	Dilute sulfate solution	Flue gases scrubbed with seawater on a once-through system, diluted, oxidized and neutralized, and discharged back to sea.	Commercial operation on small oil-fired boilers in Norway.

Table 2.2. SUMMARY DESCRIPTION OF FGD PROCESSES - GYPSUM CATEGORY

FGD process (year of first use)	Primary reagent	Product for disposal or sale	Operating principles	Present status
5 Limestone/gypsum (1973)	$CaCO_3$	gypsum	Flue gases scrubbed with limestone slurry. Resulting Calcium-sulfur compounds are air-oxidized to gypsum, separated and dewatered.	Commercial operation (coal and oil), principally in Japan.
6 Lime/gypsum (1964)	CaO	gypsum	Flue gases scrubbed with slurry of hydrated lime. Resulting Calcium-sulfur compounds are air-oxidized to gypsum, separated and dewatered.	Commercial operation (coal and oil), principally in Japan; also recently in W. Germany.
7 Double alkali/gypsum (1973)	NaOH or Na_2CO_3 and CaO or $CaCO_3$	gypsum	Flue gases scrubbed with alkaline Na compounds in solution. Used solution regenerated with lime or limestone in separate reactor and the insoluble Calcium-sulfur compounds are air-oxidized to gypsum, separated and dewatered.	Commercial operation on oil-fired boilers in Japan.
8 Dilute sulfuric acid/ gypsum (Chiyoda) (1972)	H_2SO_4 and $CaCO_3$	gypsum	Flue gases are scrubbed with dilute sulfuric acid containing ferric ion catalyst. Air oxidation produces more sulfuric acid, which is bled off and neutralized with limestone. The gypsum is separated and dewatered.	Commercial operation on oil-fired boilers in Japan.

Table 2.3. SUMMARY DESCRIPTION OF FGD PROCESSES - REGENERATIVE CATEGORY

FGD process (year of first use)	Primary reagent	Primary product	Operating principles	Present status
9 Sodium sulfite (Wellman-Lord) (1971)	Na_2CO_3 NaOH	SO_2	Flue gases are scrubbed with sodium sulfite solution and the resulting sodium bisulfite is thermally regenerated to sodium sulfite and SO_2. The SO_2 is then further treated to yield marketable products such as sulfuric acid or sulfur.	Commercial operation on oil-fired boilers in Japan. Recent commercial application on coal-fired boilers in U.S. Also on chemical/oil refinery plants.
10 Magnesium oxide (1971)	MgO	SO_2	Flue gases scrubbed with slurry of hydrated magnesium oxide. Insoluble magnesium sulfite is separated and calcined for recycle of MgO and generation of SO_2 for further treatment.	Commercial operation on oil-fired boilers in Japan. Demonstration plant on coal-fired boiler in USA.
11 Carbon adsorption (1974)	Carbon	SO_2	SO_2 from flue gases is adsorbed on activated carbon, which is then regenerated thermally, releasing SO_2 for recovery.	Demonstration.
12 Copper oxide (Shell) (1973)	CuO	SO_2	SO_2 from flue gases is adsorbed on copper oxide coated alumina. This is then treated chemically to regenerate the adsorbent and produce SO_2 for recovery.	Demonstration.

3.0 CURRENT STATUS OF OPERATING FGD SYSTEMS

There are now 144 known FGD systems operating on fossil-fueled combustion sources. Of these, 74 are operating on power utility boilers, representing about 70 x 10^6 Nm^3/h of flue gas capacity from about 20 GW generation. The remainder are operating on industrial combustion sources, principally boiler plants, but also on iron ore sinter plants and petroleum refinery plants.

In the NATO-CCMS Process Status Reports, 35 FGD systems were surveyed. Although it was originally desired to include only the larger, commercially available installations with adequate operating experience, it was necessary to include data on some smaller scale operations and some that had been installed originally for demonstration purposes in order to provide sufficient comparability between the various processes. Table 3.1 summarizes the application of the various FGD processes and gives the number of systems in operation, planned, or in the construction stage, and those closed down as of late 1977.

Table 3.2 summarizes basic technical data on the FGD systems surveyed in this study and presents information on fuel burned and system operation.

3.1 THROWAWAY PROCESSES

This category includes the three processes that produce a calcium sulfite/sulfate sludge and also the seawater scrubbing process. The sludge processes are becoming the most widely used FGD systems; 30 systems are in operation and 53 are planned or under construction. They have been used successfully on both

Table 3.1. SUMMARY OF FGD APPLICATIONS AS OF DECEMBER 1977

FGD process	Number of surveyed systems and (MW_e) served[b]	Total known operating FGD systems[a]		Number of systems known to be:	
		On power utilities and (MW_e) served	On industrial boilers	Planned/under construction	Closed down
Limestone/sludge	3 (1645)[c]	13 (5640)[d]	0	31	10
Lime/sludge	6 (2098)	11 (3125)	1	16	6
Double alkali/sludge	2 (52)	1 (20)	4	6	2
Seawater scrubbing	1 (50)[e]	0 (0)	1[f]	0	0
Limestone/gypsum	6 (4105)	23 (5511)	10[g]	0	0
Lime/gypsum	2 (787)	11 (1800)	10[h]	4	0
Double alkali/gypsum	4 (646)	7 (1949)	18[i]	0	0
Dilute sulfuric acid/gypsum	2 (373)	4 (1100)	10[j]	0	1
Sodium sulphite	2 (335)	4 (810)	13[k]	3	1
Magnesium oxide	4 (851)	1 (120)	1[l]	1	3
Carbon adsorption	2 (70)	0	1	0	2
Copper oxide	1 (36)	0	1	0	0

[a] Excludes units smaller than 60,000 Nm^3/h (19.2 MW_t) in Japan, which are unreported in the literature. This small size group may include as many as 500 small commercial non-regenerable sodium based scrubbing systems averaging 20,000 Nm^3/h. In the U.S. there are 3 utility boilers and about 90 non-utility boilers in operation using non-regenerable sodium based systems.

[b] FGD systems. Some systems serve more than one boiler. MW served is the design size of the FGD system not of the boiler.

[c] Sherburne County submitted data on Boilers 1 and 2 totaling 1,440 MW but only one unit was considered at 710 MW.

[d] Includes Shawnee 10A and 10B experimental lime/limestone units.

[e] 3 boilers and 3 systems at one location.

[f] In addition, one system installed on a source other than a boiler (approximately 16 MW unit).

[g] As many as 10 other units are operating on sintering furnaces, glass furnaces and kilns.

[h] In addition, 30 systems installed on processes other than boilers i.e. sintering machines, H_2SO_4 plants, diesel engines, smelters, glass furnaces, and incinerators.

[i] In addition, 5 systems installed on sources other than boilers.

[j] In addition, 3 systems installed on sources other than boilers.

[k] In addition, 10 systems installed on sources other than boilers, e.g., Claus furnaces.

[l] In addition, one copper smelter is operating in Japan.

Table 3.2 SUMMARIZED DATA ON FGD SYSTEMS INSTALLED ON BOILER PLANTS

FGD process	No. of systems surveyed	MWe range[a]	Predominant fuel		Reported SO_2 removal efficiency range[b], %	Reported plant availability range[b], %	Process capacity range, Nm^3/s[c]
			Type	% Sulfur			
Limestone/sludge	3	115-820	Coal	0.5-5.4	57-92	88-94	82-108
Lime/sludge	6	65-835	Coal	0.8-4.7	70-92	83-100	28-139
Double alkali/sludge	2	20-32	Coal	0.9-5.0	90-99	80-	25-35
Seawater scrubbing	1	(50)[d]	Oil	-3.0	90-97[e]	96-99	17
Limestone/gypsum	6	250-850	Coal	0.6-2.2	90-96	97-100	103-250
Lime/gypsum	2[f]	37-750	g	2.9	80-92	96-98	35-333
Double alkali/gypsum	4	26-450	Oil	2.0-2.9	90-95	95-98.	23-355
Dilute sulfuric acid/gypsum	2[f]	20-350	g	3.6[h]	96	-100	270
Sodium sulfite	2	115-220	g	2.5-3.5	90-92	97-99	99-172
Magnesium oxide	4	95-155	g	2.0-3.8	90-95	i	102
Carbon adsorption	2	20-49	Coal	0.9-5.0	70-80	N.A.	10-42
Copper oxide	1	36	Oil	2.5	80-90	N.A.	30

[a] Range of MWe units served by FGD system.

[b] Whole numbers.

[c] Range of individual scrubber (or equivalent absorber) capacity.

[d] Equivalent MWe.

[e] Efficiency dependent on bypass (reheat) flow - see Status Report.

[f] Includes one coal-fired demonstration unit.

[g] Equal number of coal and oil firing systems were surveyed.

[h] Calculated value.

[i] Insufficient data base.

N.A. - Not available.

coal- and oil-fired plants with a wide range of fuel sulfur contents and are reported to have high SO_2 removal efficiencies, whereas plant availabilities are variable.

The double alkali process is a further development designed to overcome the scaling, plugging, and erosion problems that have been generally associated with lime or limestone systems. Double alkali systems are presently used mainly with small to medium sized boilers where the extra process equipment can be offset by lower maintenance costs.

3.2 GYPSUM PROCESSES

These processes are designed to produce a quality of gypsum that may be used in place of natural gypsum in such markets as plaster or plaster wallboard, or as a setting retarder in cement manufacture. It is expected that if sufficient markets are not available for gypsum, it will be disposed of as a solid waste. Gypsum has better settling characteristics than sludges containing calcium sulfite from the throwaway processes.

By late 1977, 92 systems were operating, of which 91 were in Japan and 1 in West Germany. They have been used successfully on both coal- and oil-fired plants and are reported to have high SO_2 removal efficiencies and high availabilities.

The gypsum processes have been applied particularly in Japan. Production of FGD-gypsum and phosphate fertilizer-gypsum has led to an annual over-supply of about 2×10^6 t/y. This gypsum over-supply and the reportedly lower cost of low sulfur fuel (desulfurized fuel oil and low sulfur crudes) are mentioned as reasons

why no new gypsum producing FGD plants will be built on oil-fired boilers.

As with the throwaway process, the double alkali and the dilute sulfuric acid processes were developed to overcome some of the operating problems originally present with the lime or lime stone scrubbing processes.

3.3 REGENERATIVE PROCESSES

Interest in the two surveyed regenerative processes that use wet scrubbing of the flue gases, i.e., the sodium sulfite and magnesium oxide processes, is largely due to the regeneration of the absorbent and production of a saleable sulfur product. No additional land area for solid waste disposal is required (beyond that for ash disposal), and raw material consumption is greatly reduced.

These processes have been successfully operated on oil-fired plants and are now being applied to coal-fired boilers. High SO_2 removal efficiencies are reported. With one of the processes (magnesium oxide), there is insufficient data to report on availability, but high availability is reported for the two Wellman-Lord systems surveyed for short periods.

The dry adsorption regenerative processes (carbon adsorption and copper oxide) are being investigated because of their potential for recovery of a sulfur by-product without the disadvantages of wet scrubbing systems, and with less energy requirement for flue gas reheat. These processes have not yet been applied on a commerical scale.

All of the regenerative processes require additional processing plants for converting the concentrated SO_2 into saleable form, e.g., by purification and liquefaction, by conversion into sulfuric acid, or by chemical reduction to elemental sulfur. The processes may be more suitable for operation near industrial areas where the sulfur products may be marketed. The wet scrubbing processes also offer the possibility of utilizing a single, centralized regeneration facility to service a number of FGD systems.

4.0 COSTS AND ENERGY REQUIREMENTS

4.1 FGD PROCESS COSTS

The cost data returned in the survey questionnaires for this study were too limited to allow valid comparisons to be made between system costs, but sufficient indications can be obtained to allow some broad conclusions relative to process costs. Clearly, specific site circumstances have a large influence on capital costs and make it difficult to separate specific process costs. Additional and more detailed cost data would be required to make meaningful comparisons.

The capital costs have been adjusted to January 1976 U.S. dollars by using factors given in Section 5 of the individual Process Status Reports, and are summarized in Table 4.1 as dollars per kWe. The small sample numbers prevent the valid use of averages and accordingly only the lowest and highest values are shown in the table. More than one capital value was available on only eight of the processes, allowing a highest and a lowest figure to be stated. With the exception of the limestone/gypsum process, the remaining seven systems all overlap a central range of $58 to $74/kW, which is that of the limestone sludge systems surveyed. Excluding the four processes for which only a single value was available, the median of the lowest values is $38.40/kW, and the median of the highest values is $76.70/kW.

Operating costs summarized in Table 4.1 are those given in the individual Process Status Reports and are based, for consistency only, on 4,000 hours per year operation. Annual fixed costs are

Table 4.1 SUMMARY OF COST DATA FOR SURVEYED FGD PROCESSES

FGD process	REPORTED COSTS				Ref[a]	Country or source of cost data
	Capital, $/kW		Operating, mills/kWh			
	Lowest	Highest	Lowest	Highest		
1. Limestone/sludge	57.6	73.9	3.8	6.9	3	All USA
2. Lime/sludge	30.1[b]	127.7[c]	2.0[c]	6.4[c]	4	[b]Japan, [c]USA
3. Double alkali/sludge	136[d]		3.71[d]		3	USA
4. Seawater scrubbing	43.2[d]		2.60[d]		13	Norway
5. Limestone/gypsum	32.7	46.0	3.64[d]		3	Japan
6. Lime/gypsum	37.8[b]	76.5[c]	3.9[b]	4.7[c]	4	[b]Japan, [c]W. Germany
7. Double alkali/gypsum	54	104	4.03	9.21	3	Japan
8. Dilute sulfuric acid/gypsum	242[d]		21.38[d]		7	USA demonstration unit only
9. Sodium sulfite	39[b]	129[c]	4.75[b]	12.8[c]	3	[b]Japan, [c]USA
10. Magnesium oxide	45[c]	102.5[b]	3.95[b]	7.15[b]	3	[b]Japan, [c]USA
11. Carbon adsorption	25[b]	75[b]	5.5[c]	-	4	[b]USA, [c]W. Germany
12. Copper oxide	130.9[d]			-	3	Japan

Note: $/kW as of January 1976.
Mills/kWh reported, on basis of 4000 hours per year operation at full load.

[a] Table number in the individual Process Status Reports.

d Only one cost reported.

Table 4.2. SUMMARY OF FGD SYSTEM ENERGY REQUIREMENTS (excluding reheat energy usage)

FGD PROCESS	as % of generation[a]		Ref[b]
	Lowest	Highest	
1. Limestone/sludge	2.9	4.0	2
2. Lime/sludge	0.9	7.1	3
3. Double alkali/sludge	2.5	5.0	2
4. Seawater scrubbing	1.1	1.5	6
5. Limestone/gypsum	0.57	3.4	2
6. Lime/gypsum	0.8	1.0	3
7. Double alkali/gypsum	1.7	2.2	2
8. Dilute sulfuric acid/gypsum	3.5	-	6
9. Sodium sulphite	2.7	9.3[c]	2
10. Magnesium oxide	1.6[d]	5.1	2
11. Carbon adsorption	-	-	
12. Copper oxide	2.4	-	App.A

[a] Energy required as % of generation estimated with the following assumptions: 0.34 overall thermal efficiency, 15% energy lost in conversion of heat to steam. For example, energy required, % =

$$\frac{(\text{steam-water}) \times \text{rate}}{(1-0.15)\ \text{generation}} \times 0.34 \times 100\%$$

or $\dfrac{(\text{natural gas rate} \times 0.34 \times 100\%}{\text{generation}}$

[b] Table number in respective process status report.

[c] Excluding 1.3% required by sulfur reduction plant.

[d] Excluding calciner.

a major part of the total annual costs, and so the operating cost per kWh is very sensitive to load factors. Highest and lowest values were available for only six of the FGD processes, ranging overall from 2.0 to 21.4 mills/kWh. The median lowest and median highest values for these six processes are 3.9 and 7.0 mills/kWh, respectively. Four of the throwaway or gypsum processes overlap a narrow central range of 4.0 to 4.7 mills/kWh.

Considering the ranges of capital and operating costs, no significant differences are evident between the lime or limestone systems or between the sludge or gypsum processes. However, no information about the costs of disposal of sludges or of by-product credit, if any, for gypsum was returned.

Despite the variability and shortcomings of the overall cost data, the limestone/gypsum and seawater scrubbing processes appear likely to have the lower costs of present-day FGD processes, though the value of the regenerative process in appropriate circumstances should not be underestimated because the cost data available thus far is limited.

4.2 ENERGY REQUIREMENTS

The energy consumption of FGD process applications can be clearly divided into two distinct areas, reheat and process operation.

Reheating of the cooled, cleaned flue gases after wet scrubbing is carried out by various methods but predominantly, in the systems surveyed, by direct firing with coal or oil. The requirement for reheat will vary from site to site, and the energy

requirement in each case can be calculated by taking the specific heat of the flue gases as 1 kJ/kg°C. The surveyed systems showed a wide range of reheat temperatures (those in Japan generally up to 135°C), so the reheat energy requirements given in the Process Status Reports should not be regarded as characterizing the FGD process. Expressed as a percentage of the fuel consumption of the boiler plant, the reheat fuel requirements range from zero (for the dry regenerable process) up to 13.2 percent.

The reported process energy requirements (not including reheat) are summarized in Table 4.2, expressed as a percentage of the power generation of the utility unit. Reported figures range from 0.57 percent to 8.8 percent.+

Apart from the more obvious reasons such as the size and parameters of the boiler plant and the stage of the FGD process development, this range of energy requirements reflects considerable differences in the detail of equipment design, for example, the pressure drop across absorbers or demisters.

+ Even the relatively simple and comparable lime/limestone systems show a range from 0.57 to 7.1.

5.0 PROCESS ASPECTS NEEDING SPECIAL ATTENTION

The Process Status Reports note areas of concern, uncertainty, or need for close observance of detailed operating parameters. Some of these are relevant only to the individual process, but others are common to all FGD processes or to groups of related processes.

5.1 PROCESS DESIGN AND OPERATION[1*]

Every FGD system is a chemical processing plant in its own right and not an ancillary to the main plant (boiler unit, etc). It requires full professional design and proper training of operating staff. The complexity of the regenerative processes is obvious even from the flow sheet, but the apparent simplicity, by comparison, of the sludge or gypsum processes can be very misleading.

The chemical nature of the FGD processes and their control characteristics will be foreign to most power utility staffs, and this can amplify the problems in rectifying any operating problems and maintaining high availabilities.

The complexity and uncertainties in the chemistry of the processes and their susceptibility to variations in fuel composition (particularly with coal firing) emphasize the importance of firm adherence to prescribed operating parameters. The importance of reliable automatic controls is evident, as is the need for a routine maintenance program and accurate pH control.

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* See Table 5.1 for references to individual status reports.

Table 5.1 REFERENCES TO INDIVIDUAL PROCESS STATUS REPORT PAGE NUMBERS

FGD PROCESS	REFERENCE 1	2	3	4
1. Limestone/sludge	vi	4-4	4-2	4-4
2. Lime/sludge	0-3	2-5	2-9+ 4-2	4-3
3. Double alkali/sludge		4-5		
4. Seawater scrubbing				29
5. Limestone/gypsum	vi	2-13	v+ 3-1	
6. Lime/gypsum	0-3	4-1+ 2-5	2-5	
7. Double alkali/gypsum		4-5	4-3	4-5
8. Dilute sulfuric acid/gypsum		2-13		
9. Sodium sulfite				4-4
10. Magnesium oxide	4-5	4-5		
11. Carbon adsorption				
12. Copper oxide		4-2		

5.2 FUEL CHLORINE CONTENT[2]

The chlorine content of coals has an important impact on several areas, some of which may be crucial to the successful adoption and operating of an FGD system.

Coal chlorine is released on combustion as hydrogen chloride, which is easily absorbed in the wet scrubbers; even after neutralization a high chloride ion concentration can lead to corrosive attack. With higher chlorine coals, special construction materials will be required. The survey report data do not indicate any critical chlorine content; the coal chlorine contents reported range from 0.01 to 0.20 percent with a median of about 0.04 percent. One report states that increased scaling occurs with coal chlorine above 0.04 percent.

Only limited amounts of chloride can be accepted in recovered gypsum sold as a by-product. One report mentions a maximum of 0.5 percent. For this to be achieved without purging excess chloride to effluent disposal and creating an additional water treatment problem, the sulfur/chlorine weight ratio in the coal would need to be approximately 20:1 or higher.

In the double alkali, the sodium sulfite, and magnesium oxide processes, the purging of chlorides from the recirculating scrubber liquors causes additional losses of reagent salts.

5.3 SCALING PROBLEMS[3]

Uncontrolled formation of deposits in process vessels and scaling of absorbers and demisters are a liability in the lime and limestone processes. Several factors can influence this

tendency, and remedial measures include the geometry of the absorber, close control of pH (to within 0.5 units), seeding with gypsum crystals, use of additives, attention to the mode of addition of raw materials, and a scheduled maintenance program.

Most of the problems have been resolved, but there is still limited experience over the whole range of coal sulfur contents (especially high-sulfur coals).

5.4 OTHER ENVIRONMENTAL IMPACTS[4]

Recirculation of the scrubbing liquor leads to a continuous concentrating of all the substances extracted from the flue gases into the liquid phase. Equilibrium is established either by precipitation from saturated systems, by controlled purging of liquid from the process loop, or by a combination of these (including removal of liquid as the aqueous portion of wet solids or of sludge).

Very little information on the environmental consequences or impact of purge liquids or of leaching or drainage of soluble substances from deposited solids or sludges appears in the survey data. Purge liquids of FGD systems may contain a high chemical oxygen demand, suspended solids, and heavy metals. No general picture can be given as the constituents are dependent on fuel composition and FGD process. These potential problem areas have apparently not been studied in depth, and little was reported about these site-specific problems. The chloride content of liquid effluents, trace element concentrations, and land area

requirements for dumping are three important areas on which further information is necessary, and which can not be neglected in process design.

6.0 APPLICABILITY STUDY

As a supplement to this survey study, the NATO-CCMS Flue Gas Desulfurization Study Group is preparing an applicability study (Phase II) to assist potential users in selecting FGD systems. This study will contain detailed cost comparisons for a variety of FGD processes, boiler sizes, and fuel combinations. Also, decision aids and a rating system specifically designed for FGD processes will be developed. These decision aids will summarize advantages and problems of each system in a format that will allow direct comparison of most available FGD processes.